DESIGN OF A 20,000 K. V. A. TRANSFORMER

BY

A. S. LIU

ARMOUR INSTITUTE OF TECHNOLOGY

1920

537.832
L 74

Illinois Institute
of Technology
UNIVERSITY LIBRARIES

AT 549
Liu, A. S.
Design of a 20,000 K.V.A.
transformer

For Use In Library Only

DESIGN OF A 20,000 K. V. A. TRANSFORMER

A THESIS

PRESENTED BY

ABRAHAM SANG LIU

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

MAY 27th, 1920

APPROVED:

Professor Electical Engineering

Dean of Engineering Studies

Dean of Cultural Studies

ILLINOIS INSTITUTE OF TECHNOLOGY
PAUL V. GALVIN LIBRARY
35 WEST 33RD STREET
CHICAGO, IL 60616

Digitized by the Internet Archive
in 2009 with funding from
CARLI: Consortium of Academic and Research Libraries in Illinois

http://www.archive.org/details/designof20000kva00liua

CONTENTS.

Page.

Foreward

Introduction 1

Chapter I. 7

Methods of Design 7

(1) Bohle & Robertson 7

(2) H. M. Hobart 8

Chapter II. 11

Hobart's Method 11

Specification 12

Design Sheet 23

Procedure 28

Bibliography 46

29106

FOREWARD.

The purpose of this thesis, is the design of a 20,000 kv-a., 110,000 / 11,000 volts, single phase, 60 cycles, oil insulated, water cooled transformer, to be operated on a 110,000 volts power transmission system.

The design is purely from a practical standpoint, that is, I have supplemented theoretical considerations with practical data taken from the General Electric Company and the Westinghouse Electric and Manufacturing Company.

INTRODUCTION.

The nature of the problem of transformer design may be considered step by step.

The specification usually gives kv-a capacity, frequency, voltage, efficiency, and regulation, whilst sometimes the no-load current is specified and always of course, the cost must fall within fairly narrow limits.

If the specification involved nothing except say, the voltage, an unlimited number of designs would be possible, for the only condition would be that the ratio of the turns should be correct. The weight of copper and the weight and dimensions of the iron might have almost any values.

The specification of current as well as voltage would only make the design more definite in setting a limiting minimum to the section of the copper, since obviously the copper would have to be so thick as not to be damaged by the heat produced in it. Such a transformer would, within ordinary limits, be suitable for any frequency.

The efficiency condition, although it would sweep away the majority of the possible designs just spoken of, yet would leave a wide choice. Unless the relation of copper loss to iron loss were fixed there would still be numerous alternative designs available; some would have much copper and little iron, others much iron and little copper.

The fixing of the regulation would not greatly limit the number of possible designs, since the regulation might be varied between wide limits by simply changing the shape or the relative disposition of the primary and secondary coils, without altering the other factors.

If the magnetizing current were also fixed, a few of the otherwise possible designs would be eliminated but since a slight change in the section of the iron (producing a corresponding change in the flux density) might greatly effect the reluctance of the magnetic circuit and therefore the magnitude of the magnetizing current, with but little effect upon the ef-

ficiency or the regulation, it follows that many alternative designs would still be available.

The remaining condition -- cost -- might be satisfied by a multitude of different designs. From among those electrically available, it might be possible for instance, to choose two of equal cost, one of which, though much heavier than the other, would be much easier to assemble and therefore more economical of labor.

The line of thought just outlined is intended to show, that no matter how logical may be the design method, there is always much left to the choice or even to the mere fancy of the engineer. There are many variables whose exact value has little effect upon the specified characteristics of the apparatus and there are many different designs which will satisfy the same specification.

It is on account of this unavoidable latitude in design that such a variety of methods are in use. Since for many of the quantities involved a number of alternative values are available, all leading to good results, it is

usual to assume for such quantities trial values such as have proved satisfactory in apparatus already designed. To some extent then every practicable method of design becomes a method of trial and error.

Some designers go to the extreme of basing a design solely upon trial. Such crude methods, if coupled with patience and perseverance lead to successful results and they are popular. This is unfortunate, for such methods tend to retard progress. Improvement seldom follows, except from the intelligent understanding and this comes only from thought. The method of trial and error is essentially lavish of labor and sparing of thought. It is the method of the untrained savage and in matters of daily life the favorite method of us all. We respect its usefulness, but at the same time feel pride and pleasure in producing its converse -- the method which derives the per fect design by a logical process based upon first principles.

In transformer design trial methods are especially successful, because whilst there is difficulty in predetermining the dimensions which

shall produce a desired result there is none in predtermining with fair accuracy the results which will follow from given trial dimensions. In fact, if a man had sufficient patience and a little common sense, he might design a transformer solely by trial and error, using no more elaborate basis for his first trial design than say a random sketch.

Since it becomes impracticable owing to the impossiblity of forseeing the condition under which a given transformer may have to work, to design every transformer for maximum efficiency it is neccessary to make a compromise and a safe compromise is to design for minimum cost whilst using high densities both of current and flux.

Electrical losses are more important in the case of large transformers than in that of small ones, for the large transformers cost less per kv-a and electrical losses form a large part of the total loses. The large transformers are however at a disadvantage in that the cost of attending and cooling water or air blast must be added to interest and depreciation. Also it is a question whether strictly interest and depreciation on the switch gear and instruments needed for the trans-

former ought not to be set down in the expression for commercial efficiency.

In this case the electrical losses would become even less important for the large transformers than for the small ones.

The strictly logical design would be based upon commercial efficiency as thus defined. But in designing a line of transformers for competition in the open market the items of interest and depreciation, and cost of floor space and attendance are variable; they depend upon the part of the world in which the transformer will be used as well as upon the local conditions in the factory or station in which it is to be installed and upon many other things. The logical design is possible when only all such details are definitely stated in the specification.

To get out a special design for each individual transformer would however, add greatly to the cost of production and in most cases the interest upon this extra cost would be more than the money saved by the improvement in commercial efficiency.

CHAPTER I.

METHODS OF DESIGN.

During the past four years the following six books have been published dealing with a specific method of prodedure in the design of alternating current static transformers : (1) Bohle and Robertson, "Treatise on Transformers", 1915; (2) Hobart, "Design of Static Transformers", 1911; (3) Ryan, "Design of Electrical Machinery", 1912; (4) Barr and Archibald, "Alternating Current Machinery", 1913; (5) A. Gray, "Electrical Machine Desing", 1913; (6) Pender, "American Handbook for Electrical Engineers", 1914.

On analyzing the methods advocated in these books it will be seen that there are in reality two distinct methods advocated.

Method 1. Bohle and Robertson.

The fundamental general equations of the transformer are differentiated and a set of tables and curves deduced from which it is possible to make a preliminary design, assuming

kv-a, core loss, copper loss, quality of the iron, temperature of the copper, space factor of the winding, space factor of the iron, and a ratio of cost per unit volume of copper space to cost per unit volume of iron space, this preliminary design giving a transformer which will cost the least money to build under the conditions assumed.

If the assumed ratios of core loss to kv-a is too great for the volume of iron calculated, the temperature of the iron will be too great or the magnetizing current will be too great.

To correct this it will be necessary to redesign the transformer, assuming a less core loss.

Method 2. H. M. Hobart.

The preliminary assumptions are the kv-a, copper loss, iron loss, quality of the iron, temperature of the copper, and space factor of the iron, and in addition the assumptions deduced from commercial practice and set forth in the form of curves and tables, comprising volts per turn, widths of window, maximum flux density and space factor of copper.

Using these preliminary assumptions in a set of simple and well recognized algebraic formulas, the designer can lay out a preliminary design which must later be recalculated and slightly revised, since all the preliminary assumptions made are not compatible with each other.

With this method there is no means of knowing whether the geometrical shape finally deduced is that which fulfills the specification for a minimum cost.

Ryan advocates Method 2, except that he makes no preliminary assumption of copper space factor and width of window, but he does make a vague assumption of geometrical shape substantially as shown in a set of cuts.

Barr and Archibald advocate what amounts to Method 2, but instead of giving tables and curves they endeavor to deduce the general formula from calculating each case. They neglect to use calculus at one step but instead use a very laborious graphical solution. They also make the mistake of assuming that the cheapest transformer is obtained when the costs of active iron and copper are equal. That this is a fallacy is shown by

Bohle and Robertson (page 561). Values given by their equations are for this reason slightly incorrect.

Gray advocates Method 2 except that no preliminary assumption of the copper loss. Slichter, in the "American Handbook for Electrical Engineers", advocates Method 2, except that he makes a further preliminary assumption of current density and ampere turns per inch of core.

Comparing Method 1 with Method 2, it is the opinion of several designers that Method 1 should be superior if the data were correctly set forth in a form easily understandable by the designers, since Method 1 proceeds from a minimum of preliminary assumptions directly to all dimensions and data by one set of calculations and arrives at a construction involving a minimum cost to fulfill the preliminary assumptions. In Method 2 recalculations are usually necessary and when the final result is reached the geometrical shape will not in general be that which gives the least cost, although it may be far from the most economical design.

CHAPTER II.

IN the following pages, the design is based on Method 2, as given in the preceeding chapter.

Design of a single phase, shell type, 20,000 kv-a oil insulated, water cooled, transformer, for use on a 110,000 volt power transmission system.

SPECIFICATION.

OUtput	20,000 kv-a
Number of phases	One
High tension voltage	110,000
Low tension voltage	11,000
Frequency	60
Maximum efficiency to occur at full load and not to be less than	99%
Voltage regulation on 80 % p. f.	5.4
Temperature rise after continuous full load run	55°C
Test voltage: High Tension to case and Low Tension coils	220,000
Low tension winding to case	20,000

The transformer will be of the oil insulated, water cooled type, for outdoor service.

(1) NORMAL RATING:

The transformer is rated at 20,000 kva, single phase, 60 cycles, with high voltage winding for 110,000 volts and low tension winding for 11,000 volts. The transformer is to be operated on a three-phase system in banks consisting of three

transformers.

(2) PERFORMANCE:

The efficiency at 100% power factor and at 75°C will not be less than:

For 1/2 load -------- 98.8%
" 3/4 " -------- 98.9%
" full " -------- 99.2%

The regulation at normal load will not be greater than 5.4% at 80% power factor.

The inherent reactance of the transformer will be approximately 6.5% at normal rating.

The ratios of transformation are based on no-load operation and they will be subject to the effect of regulation at the various loads and power factors. The efficiency and regulation guarantees are based on normal rating.

The efficiencies are based on wattmeter measurements of the losses in the windings and in the core. The copper loss will be corrected to a temperature of 75° C. The core loss will be measured on a circuit having an E. M. F. wave form approximating a sine shape.

With constant normal voltage impressed on the primary winding and with the secondary winding

delivering its normal full load current, the per cent rise in the secondary voltage, when the load is thrown off, will not exceed the values given. The regulation will be calculated from copper loss and impedance measurements corrected to 75° C.

The temperature rise of the transformer windings above the temperature of the cooling medium, as determined by the resistance method, will not exceed 55° C. The temperature rise is for operation at full load and at the ratio of 110,000 / 11,000 volts and is based on a standard temperature of 25° C for the cooling water. The coils will be insulated with material which will withstand continuously a maximum temperature of 105° C without injury.

(3) INSULATION TESTS:

The transformer will be given an insulation test between the high voltage winding and the low voltage winding, and between the high voltage winding and iron of 220,000 volts for one minute. Between the low voltage winding and iron, a test voltage of 20,000 volts for one minute will be applied. The transformer will be tested at 100%

over-voltage in excess of normal voltage for one minute at suitable frequency.

All tests will be made in accordance with the Standardization Rules of the American Institute of Electrical Engineers except as my be stated otherwise in this specification. The procedure followed in making tests will be in accordance with the testing rules of the Westinghouse Electric and Manufacturing Company.

When more than one transformer is furnished in accordance with this specification, the average of the losses of all the transformers is to be taken as determining the efficiencies and regulation. Complete temperature tests will be made on two transformers and the average results of these two tests are to be taken as determining the temperature rises.

(4) WINDINGS:

The windings will be made up of coils subdivided into groups of high tension and low tension coils.

The high tension winding will be made up of a number of flat coils to keep the voltage stress-

es between coils low. Each coil will be wound up with layers of thin copper ribbon but with only one turn for each layer, to keep the voltage stresses between adjacent turns low. This ribbon is bare, but as the coil is wound, the conductor is automatically and continuously insulated with layers of paper and cloth applied through a folding tool. The insulating material is cut somewhat more than three times the width of the conductor so that it forms not a butt joint but a complete casing folded around the conductor with the edges lapped over the full width. The outside layer is of cambric cloth. This insulation is reinforced gradually towards the line ends of the coil until the last four turns adjacent to the line terminals are insulated to withstand the voltages incident to high frequency disturbances on the line.

The low tension coils will be made up of several rectangular copper conductors, each conductor being covered with two layers of cotton insulation. Each layer is made up of a single conductor so that the thickness of the coil is the width of the conductor. Strips of insulating

material are wound into the coil between turns.

(5) TREATMENT OF COILS:

Each coil is pressed to exact dimensions in a former and is then individually dipped in insulating varnish and baked a sufficient number of times to acquire a hard glossy surface. The varnish penetrates the insulation of the coils, binding the turns into solid and substantial coils which can easily be handled and assembled without fear of displacing any of the turns. No tape is used on any of the coils. Coils of this description transmit the heat from the interior of the coil with the least difference of temperature between copper and oil and hot spots are not present.

(6) ASSEMBLY OF COILS:

Groups of high and low tension coils are assembled together with barriers of high grade insulating sheets, and with angles and channels of the same material. All of this material is made to drawing and each piece fits properly in its place. Any part can be replaced quickly and with assurance that it will fit. When assembled, the transformer is dried out by the vacuum process and

this insulating material is then thoroughly impregnated with oil, giving it a high dielectric strength.

Ample ducts formed by inserting spacing strips or insulating material between coils are provided to allow the flow of oil along the faces of the coils. These strips are out in form of curves or "waves" and the channels fitting over the edges of the coils are cut out to correspond. With these "wavey" spacing strips, (1) continuous ducts offering very little resistance to the flow of oil are formed; (2) no conductor is covered up by the strip for a complete turn but a large percentage of the length of every turn is exposed to the cooling oil; (3) better support for the coils against short circuit stresses is afforded than with any other spacing device in use.

(7) CORE:

The core will be made up of a high grade of laminated sheet steel, carefully annealed and non-aging.

(8) END FRAMES AND COIL BRACING:

Substantial end frames for supporting and making a unit of the core and windings will be

furnished. The upper end frame will be provided with lugs or eye bolts so that the core and coils can lifted and handled. The lower end frame will be provided with feet so that the core and coils can be set down without the use of external supp orts.

To protect the coils against movement due to the mechanical stresses which tend to separate the coils if the transformer should become short-circuited, heavy boiler iron plates are placed against the flat sides of the coils where they extend beyond the iron core. Heavy tie bolts passing through the ends of the plates hold them firmly against the coils and clamp the entire set of coils together. The short-circuit stresses are by this means transmitted to the tie bolts which are of such size as to withstand the maximum stress that can be developed.

To neutralize the stresses acting in a plane parallel to the face of the coils and tending to separate the primary and secondary coils in that direction, T-beams are inserted through the group of coils at the top and bottom of the opening. Heavy bolts at the ends of these T-beams serve to

force them apart and to brace the coils effectively in this direction.

(9) CASE:

The tank will be substantially constructed of boiler plate and boiler iron cover will be securely bolted to the top. A gasket will be placed between the tank and the cover, making it air-tight. Suitable means will be provided so that case, transformer and oil may be handled as a unit.

A suitable base will be provided with wheels to allow rolling the transformer in a direction perpendicular to a line through the high tension bushings. Rail gauge to be determined later.

(10) HIGH TENSION TERMINALS:

The leads and taps from the high tension coils are connected to terminals which are carried by insulating supports mounted on the insulating barriers between coils. This forms a very substantial terminal arrangement, entirely free from the grounded supports of the usual terminal board. Connections between the various taps and the outgoing leads will be made at

these points.

The two outgoing leads will be carried through the cover through terminals of the well-known condenser type. They are small and compact and their service record shows them to be the most rugged and durable terminals on the market.

(11) LOW TENSION TERMINALS:

Two low tension terminals will be brought through the cover. A terminal bar insulated with a heavy micarta tube will be mounted inside the transformer case carrying terminals connected to the low tension winding. The outgoing leads will be connected at this point.

(12) DETAILS:

A valve will be provided near the bottom of the case by means of which the oil can be quickly withdrawn. A gauge will be provided at the top to show the height of the oil and a pet cock at the bottom for testing samples of the oil. An indicating dial type thermometer will be mounted on the side of the case, with its bulb projecting into the hot oil. It will be supplied with adjustable electrical contacts which can be used to operate an alarm if the temperature of the oil should

exceed 65° . A vent provided with a thin diaphragm will be placed in the cover so that if an excessive internal pressure should occur it will be relieved by the rupture of the diaphragm.

One and one-fourth inch pipe connections will be provided at the top and bottom of the case to which permanent connections can be made to a filter system for cleaning and drying the oil.

The cooling coil will be helical in form and will be placed near the top of the oil. All connections through-out the portion within the case will be welded or brazed. After being formed, they will be tested with a hyrdraulic pressure of 600 pounds per square inch.

DESIGN SHEET.

Items.	Symbol.	Values.
1. Volts per turn	V_t	188
Low Tension Winding.		
2. Total number of turns	T_s	56
3. Number of coils		8
4. Number of turns per coil		7
5. Secondary current, amperes	I_s	1818
6. Current density, amperes per square inch	Δ	1890
7. Cross section of each conductor, square inches		6 strips each .456 x .35 = .956
8. Insulation of wire cotton tape, inches		.075
9. Insulation between layers, in.		.225
10. Number of turnsper layer, per coil		1
11. Number of layers		7
12. Overall width of finished coil, inches		0.5
13. Thickness (or depth of coil with allowance for irregularities and bulging at center, inches		21.5

DESIGN SHEET.

	Items.	Symbol.	Values.
	High Tension Winding.		
14.	Total number of turns	T_p	560
15.	Number of coils		24
16.	Number of turns per coil		24 in 22 coils. 16 in 2 coils.
17.	Primary current, amperes		181.8
18.	Current density, amperes per square inch	Δ	1920
19.	Cross section of each wire, square inch		.43 x .22 = .0946
20.	Insulation on wire (cotton coverying) inch		0.128
21.	Insulation between layers fullerboard, inch		.06
22.	Number of turns per layer per coil		1
23.	Number of layers in all but end coils		24
24.	Overall width of finished coil, inch		0.4
25.	Thickness of depth of coil, inches		15
26.	Sketch of assembly coils, with necessary insulating spaces and oil ducts, see Fig. 1		
27.	Size of window or opening for windings, inches		23 x 60

DESIGN SHEET.

Items.		Symbol.	Values.
	Magnetic Circuit.		
28.	Total flux (maxwells)	ø	7.57×10^7
29.	Maximum value of flux density in core under windings (gausses)	B	13,920
30.	Cross section of iron under coils, square inches		820
31.	Number of oil ducts in core		none
32.	Width of oil ducts in core		none
33.	Width of stampings under windings, inches	L	20
34.	Net length of iron in core,		41
35.	Gross length of core, inches	S	46
36.	Cross section ofiron in magnetic circuit outside windings, square inches		820
37.	Flux density in core outside windings, (gausses)	B	13,920
38.	Average length of magnetic circuit under coils, inches		206
39.	Average length of magnetic circuit outside coils, inches		206
40.	Weight of core, lb.		46,300
41.	Losses in the iron, watts	W_i	82,400

DESIGN SHEET.

Items.		Symbol.	Values.
	Copper Losses.		
42.	Mean length per turn of primary, feet		19.66
43.	Resistance of primary winding, ohms	R_1	1.245
44.	Full-load losses in primary (exciting current neglected)		41,150
45.	Mean length per turn of secondary, feet		19.66
46.	Resistance of secondary winding, ohms	R_2	0.1245
47.	Full load losses in secondary, watts		41,150
48.	Total full load copper losses, watts	W_c	82,300
49.	Total weight of copper in windings, lb.		8,100
50.	Efficiency at full lead (unity power factor)		99.4
51.	Efficiency at full load 80 % power factor		98.4
52.	No-load primary exciting current, amperes	I_c	12.1

DESIGN SHEET.

Items.	Symbol.	Values.
Regulation.		
53. Reactive voltage drop	I_1X_p	530
54. Equivalent ohmic voltage drop	I_1R_p	2485
55. Regulation on unity power factor		2.26
56. Regulation on 80 per cent power factor		4.1
Design of Tank. Cooling Surfaces.		
57. Effective cooling surface of tank, square inches		386,000
58. Number of watts dissipated from tank surface		92,620
59. Watts to be carried away by circulating water		72,080
60. Size and length of pipe in cooling oil		1 1/4 x 1500
61. Approximate flow of water per minute, gallons		18.02
62. Approximate weight of oil, pounds		83,250
63. Estimated total weight of transformer, pounds		250,000

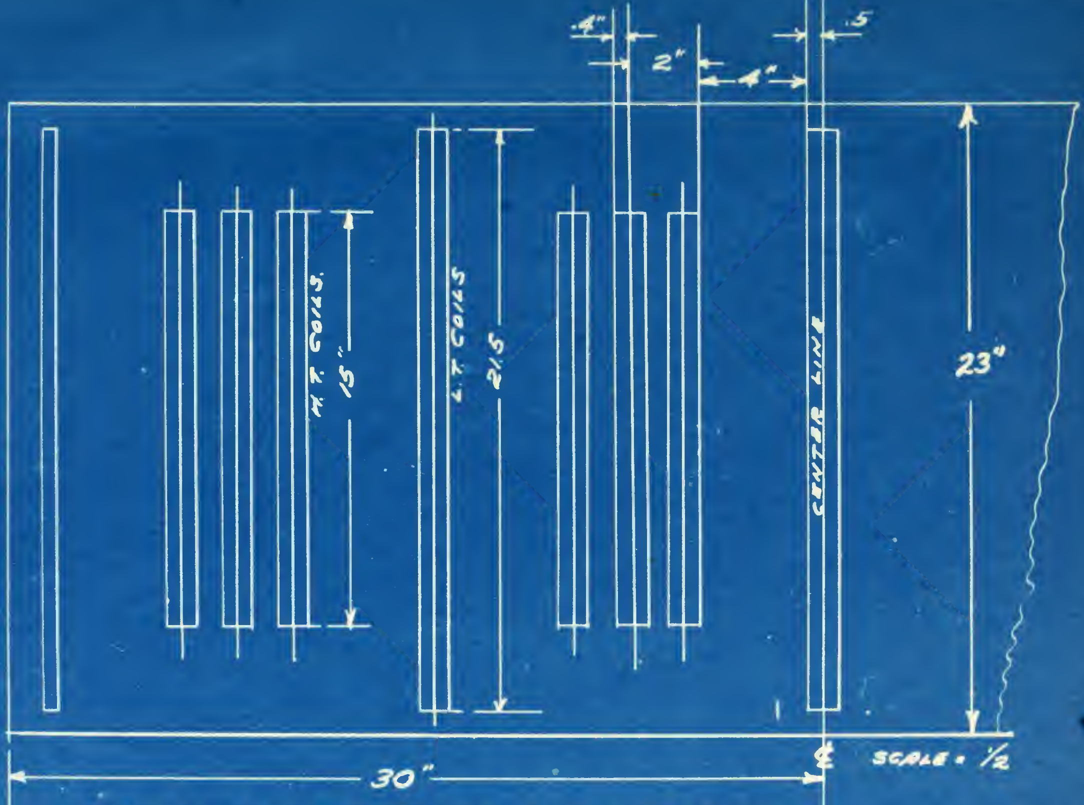
Items (1) and (2). Low tension winding. The volts per turn for a shell-type power transformer are $V_t = c\sqrt{\text{volt-ampere}}$ output, where c is an empirical coefficient based on data taken from practical designs. Westinghouse gives c as 0.042. Or $V_t = .042\sqrt{20,000,000} = 187.9$ say 188. Whence $T_s = 11,000 / 188 = 58.5$.

Items (3) and (4). The number of separate coils is determined by the following considerations: (a) The voltage per coil should preferably not exceed 5000 volts; (b) The thickness per coil should be small (usually within 1.5 inches) in order that the heat may readily be carried away by the oil or air in the ducts between coils; (c) The number of coils must be large enough to admit proper subdivision into sections of adjacent primary and secondary coils to satisfy the requirements of regulation by limiting the magnetic flux linkages of the leakage field; (d) An even number of low tension coils is desirable in order to provide for a low-tension coil near the iron at each end of the stack.

To satisfy (a) there must be at least 110,000/4600 = (say) 24 high tension coils. If an equal

number of secondary coils were provided, we could, if desired, have as many as twenty-four similar high-low sections which would be more than necessary to satisfy (c). The number of these high-low sections or groupings must be estimated now in order that the arrangement of the coils, and the number of secondary coils, may be decided upon with view to calculating the size of the "windows" in the magnetic circuit. It is true that the calculations of reactive drop and regulation can only be made later; but these will check the correctness of the assumptions now made and the coil groupings will have to be changed if necessary after the preliminary design has been carried somewhat further. The least space occupied by the insulation and the shortest magnetic circuit, would be obtained by grouping all the primary coils in the center, with half the secondary winding at each end, thus giving only two high-low section; but this would lead to a very high leakage reactance and regulation much worse than the specified 6 per cent.

Experience suggest that about eight high-



SECTION THRU WINDINGS AND INSULATION.

FIG. 1.

low sections should suffice in a transformer of this size and voltage, and will try this by arranging the high tension coils in groups of six and providing eight secondary coils (see Fig. 1.). This gives for item (4) 58.5 / 8 = 7.19 say 7; hence $T_s = 56$.

Items (5) to (13). The secondary current is $I_s = 20,000,000 / 11,000 = 1818$ amperes. A reasonable value for the current density is about 1900 or 1818 / 1900 = 0.956 sq. in. for the cross section of the secondary conductor.

In order to decide upon a suitable width of copper in the secondary coils, it will be desirable to estimate the total space required for the windings, so that the proportions of the "window" may be such as have been found satisfactory in practice. The copper space factor is the ratio between the cross section of copper and the area of the opening or "window" which is necessary to accomodate this copper together with the insulation and oil or air ducts. Assume the space factor to be about 0.10 then the are of the window = 2 x 56 x 0.956 / 0.1 = 1070 sq. in. From Fig. 2, if H = 2.5 times D, then 2.5 D

$x\ D = 1070$ or $D = 20.68$ inches. Make it 21 in.

The clearance between copper and iron under oil for a working pressure of 11,000 volts is given by the following formula:

$$0.25 + 0.05 \times kv$$

or $$0.25 + 0.05 \times 11. = 0.8 \text{ in.}$$

For the insulation between layers, use 0.02 inch for cotton, and a strip of 0.012 inch fuller board, making a total of $7 \times 0.031 = 0.224$ in. The thickness of each secondary conductor will therefore be about $21\ (0.8 + 0.224 + 0.8) = 2.74$ inches which gives a width of $0.956 / 2.74 = 0.349$ inch. Let this be 0.35 inch and build up each conductor of six strips 0.456 inch thick with 0.018 paper between wires (to reduce eddy current loss) and cotton tape outside. Allowing 0.075 inch for cotton tape and 0.036 inch for a strip of fuller board between turns, the total thickness of insulation measured across the layers is

$$7 \times (0.075 + 5 \times 0.036) = 1.785 \text{ inches.}$$

A width of window of 23 inches (Fig. 1) will accomodate these coils. The current density with this size of copper is

$$\Delta = 1818 / 6 \times 0.456 \times 0.35 = 1890.$$

Items (14) to (25). High tension winding. T_p = 56 x 110,000 / 11,000 = 560. This may be divided into 22 coils of 24 turns each and 2 coils of only 16 turns each, which would be placed at the ends of the winding and provided with extra insulation between the end turns.

The formula 0.25 + 0.03 kv gives the thickness of insulation -- consisting of partitions of fullerboard with spaces between for oil circulation --separating the high tension copper from the low tension coils or grounded iron. 0.25 + 0.03 x 110. = 3.55 inches. Make this clearance 4 inches. Then since the width of opening is 23 inches, the maximum permissable depth of winding of the primary coils will be 23 - 8 = 15 inches. The primary current (item 17) is I_p = 20,000,000 / 110,000 = 181.8 amperes. The cross section of each wire is 181.8 / 1900 = 0.0956 sq. in. Allowing 0.128 inch for the total increase of thickness due to the cotton insulation and 0.06 for a strip of fullerboard between turns, the thickness of the copper strip (assuming flat strip to be used) must not exceed (15 / 24) - 0.188 = 0.437 inch

which makes a width of copper equal to 0.0956 / 0.437 = 0.218 inch. Try copper strip 0.43 x 0.22 = 0.0946, making the current density equal to 1920.

The two end coils with fewer turns would be build up to about the same depth as the other coils by putting increasing thickness of insulation between the end turns. Thus since there is a total thickness of copper equal to 0.437 x (24 - 16) = 3.496 inches to be replaced by insulation, gradually increase the thickness of fullerboard between the last eight turns from 0.06 inch to 0.75 inch.

Items (26) and (27). Size of opening for windings. Figure 1, shows the cross section thru the coils and insulation. Oil ducts not less than 1/4 in. or 5/6 inch wide are provided near the coils to carry off the heat, and the large oil spaces between the high tension coils and the low tension coils and iron stampings are broken up by partitions of pressboard, or ~~ther~~ similar insulating material as indicated.

In this manner the second dimension of the window is obtained. This is found to be 60 inches, whence the copper space factor is

$$\frac{(560 \times 0.0956) + (56 \times 0.956)}{23 \times 60} = 0.0775.$$

Items (28) to (41). The magnetic circuit. The virtual value of the induced primary volts will $E = 4.44 \, f \, \phi \, T_p / 10^8$, if we assume the flux variations to be sinusoidal, (the form factor is 1.11). Rewriting for ϕ, we get,

$$\phi = 110,000 \times 10^8 / 4.44 \times 60 \times 560$$

$$\phi = 7.375 \times 10^7.$$

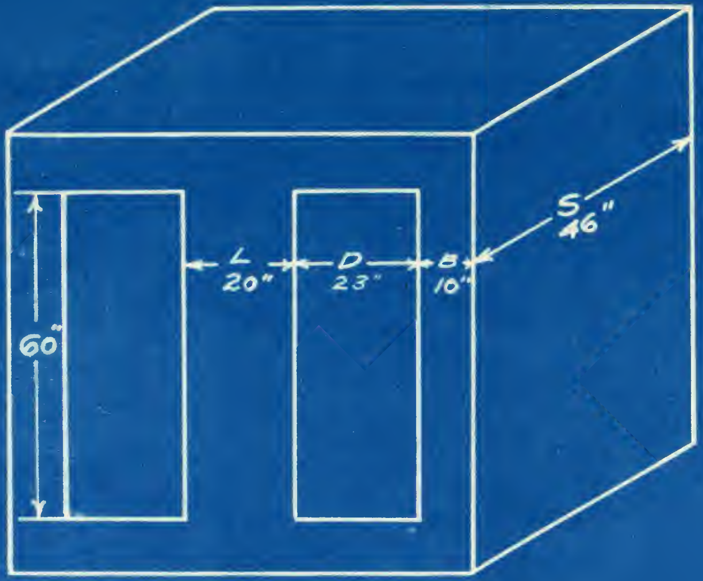
Before assuming a flux density for the core, the permissible losses were first calculated. The full-load efficiency being .99 the total losses are $20,000,000 \times (1 - .99) / .99 = 201,500.$

To obtain maximum efficiency at full-load in a power transformer, the ratio of copper loss to iron loss W_c / W_i should be about $^b = 0.925$. The factor b is determined as follows: The sum of the losses is $W_c + W_i$ but $W_c = I^2R = (kva)^2R / E^2$ $=$ a constant $/ E^2$; and $W_i \propto B^2$. Also, since f remains constant, $E \propto B$ and we can write $W_i =$ a constant $\times E^2$. The quantity which must be a maximum is therefore

$$\text{a constant} / E^2 + \text{a constant} \times E^n.$$

If we take the differential coefficient of this function of E and put it equal to zero, we get the relation $W_c / W_i = n / 2$. The value of

ASSEMBLED STAMPINGS OF SINGLE PHASE SHELL TYPE TRANSFORMER.



SCALE = 1/10

FIG. 2.

n for high densities is about 2 while for low densities, it is nearer to 1.7. A good average being 1.85. Hence W_c / W_i or b = 1.85 / 2 = 0.925. W_i = 201,000 / 1.925 = 105,000. W_c = 201,000 - 105,000 = 96,500.

Assume the width of core under the windings (the dimension L of Fig. 2) to be 20 inches and the width B (Fig. 2) of the return circuit to be 10 inches. The average length of the magnetic circuit measured along the flux lines, will be $2 \times (23 + 10 + 60 + 10) = 206$. If the flux density is taken at 13,000 gausses, the cross section of the iron is $7.375 \times 10^7 / 13,000 \times 6.45 =$ 880 square inches.

The watts lost per pound (from curve Fig. 3) are w = 1.55, whence the total iron loss is $W_i = 1.55 \times 0.28 \times 880 \times 206 = 78,480$ watts, which is considerably less than the permissible loss. It is not advisable to use flux densities much in excess of the selected value of 13,000 gausses for the following reasons: (a) The distortion of wave shapes when the magnetization is carried beyond the "knee" of the B-H curve; (b) The large value of the exciting current; (c) The

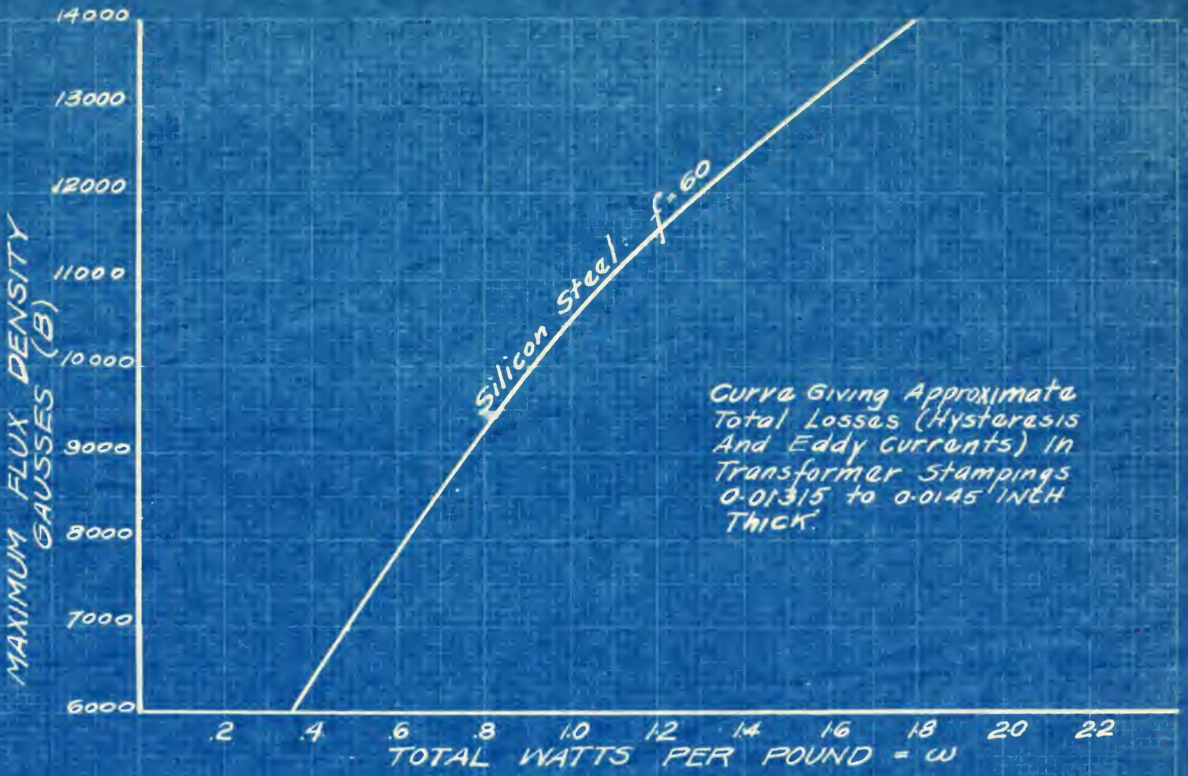


FIGURE 3 — LOSSES IN TRANSFORMER STAMPINGS.

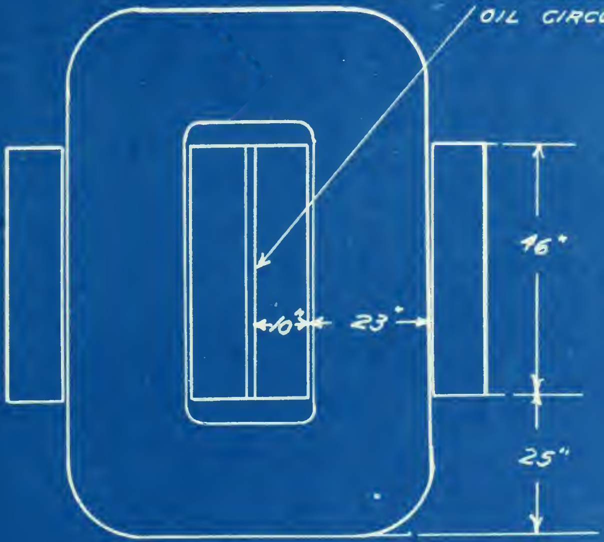
difficulty of getting rid of the heat from the surface of the iron when the watts lost per unit volume are considerable.

The design is proceeded on the basis of 14,000 gausses as an upper limit for the flux density.

If no oil ducts are provided, between sections of the stampings, the stacking factor will be about 0.89. A gross length of 46 inches (Item 35) gives 41 inches for the net length and a cross section of 41 x 20 = 820 square inches. Whence $B = 7.375 \times 10^7 / 6.45 \times 820 = 13{,}920$; and the total weight of iron is 820 x 206 x 0.28 = 46,300 pounds. The watts per pound from curve Fig. 3 are $w = 1.78$; therefore $W_i = 1.78 \times 46{,}300 =$ 82,400 watts.

Items (42) to (49). Copper losses. The mean length per turn of the windings is best obtained from Fig. 4. This sketch shows a section through the stampings parallel with the plane of the coils. The mean length per turn of the secondary as measured off the drawing is 236 inches and since the length per turn of the primary coils will be about the same, this dimension will be used in both cases.

SECTION THRU COIL AND STAMPINGS.



SCALE = 1/10

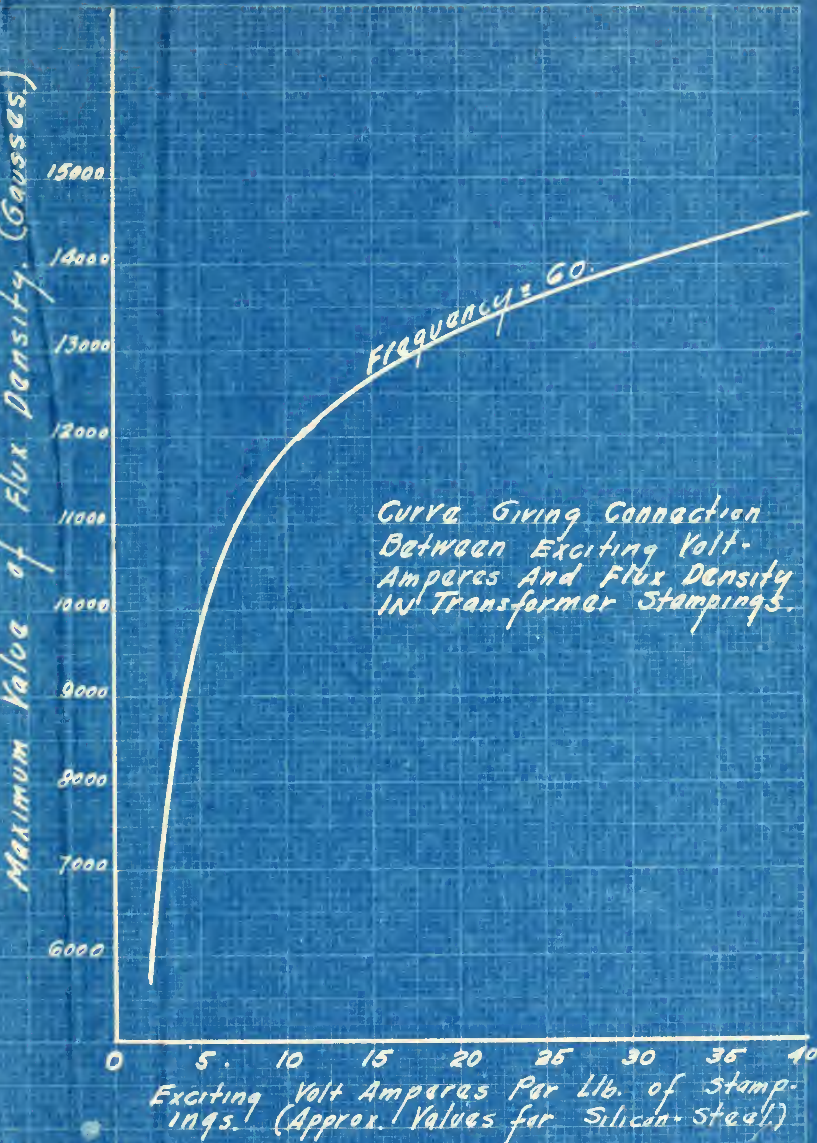
FIG. 4.

Taking the resistivity of the copper at 0.9×10^{-6} ohms per inch cube, the primary resistance (hot) is $R_1 = 0.9 \times 236 \times 560 / 10^6 \times 0.0956 = 1.245$ ohms. Whence the losses (Item 44) are $I_p^2 \times R_1 = 181.8^2 \times 1.245 = 41,150$ watts. For the secondary winding we have $R_2 = 0.9 \times 236 \times 56 / 10^6 \times 0.956 = .1245$ ohm; whence the losses (Item 47) are $I_2^2 \times R_2 = 1818^2 \times .1245 = 41,150$ watts. $W_c = 41,150 + 41,150 = 82,300$ watts, which is appreciably less than the permissible copper loss.

The weight of copper (Item 49) is $(236 \times 560 \times 0.956 + 236 \times 56 \times 0.0956) \times 0.32 = 8,100$ pounds.

Items (50) to (51). Efficiency. The full load efficiency on unity power factor is $20,000,000 / 20,000,000 + 82,300 + 82,400 = 0.994$. The full load efficiency on 80 per cent power factor is $20,000,000 \times 0.8 / 20,000,000 \times 0.8 + 164,700 = .989$.

Item (52). Open circuit exciting current. Using curve of Fig. 5, we obtain for a density of $B = 13,900$, the value of 18.75 per pound of core. The weight of iron (Item 40) being 45,300 pounds, it follows that the exciting current is



Curve Giving Connection Between Exciting Volt-Amperes And Flux Density IN Transformer Stampings.

FIG. 5.

I_e = 46,300 x 28.75 / 110,000 = 12.1 amperes. This is 6.65 % of the load component.

Items (53) to (56). Regulation. Referring to Fig. 1, it is seen that there are eight high-low sections, all about equal, since the smaller number of turns intwo out of twenty four primary coils is not worth considering in calculations which cannot in any case be expected to yield very accurate results.

The expression for the inductive voltage drop is (all dimensions are expressed in centimeters)

$$I_1X_1 = \frac{2\pi f \times 0.4\pi T_1^2 \times I_1 \times l}{10^8 h}\left[g + (p + s / 3)\right]$$

where T_1 = 560 / 8 = 70;

I_1 = 181.8,

l = 236 x 2.54 = 600 (mean length per turn of the winding.),

h = 23 x 2.54 = 58.4 (height of window),

g = 4 x 2.54 = 10.16 (space between high tension copper and low tension coils),

p = 2 x 2.54 = 5.98 (thickness of one half of primary coil),

s = 0.5 x 2.54 = 1.27 (thickness of half secondary coil),

$$I_1X_1 = \left(2\pi \times 60 \times 0.4\pi (70)^2 \times 181.8 \times 600 \;/\; 10^8 \times 58.4\right) \times 10.16 \left[5.08 + 1.27 / 3\right]$$

$$= 43.2 \times 12.27 = 530 \text{ volts.}$$

Since there are eight sections and all the turns are in series, the total reactive drop at full load is $I_1X_p = 530 \times 8 = 4{,}240$ volts, which is only 3.86 per cent of the primary impressed voltage.

The equivalent primary resistance is given by the following expression, $R_p = R_1 + R_2 (T_p/T_s)^2$

$R_p = 1.245 + .1245 (560 / 56)^2 = 13.69$ ohms, or

$I_1R_p = 181.8 \times 13.69 = 2485$ volts, which is 2.26 per cent of the impressed voltage.

The following expression gives the per cent regulation (approximate)

Regulation = per cent IR cos ϕ + per cent IX sin ϕ

For unity power factor (cos $\phi = 1$)

Regulation = 2.26 + 0 = 2.26 per cent.

For 80 per cent power factor,

Regulation = $2.23 \times 0.8 + 3.86 \times 0.6 = 4.1$ %.

Items (57) to (61). Requirements for Limiting Temperature Rise. A plan view of the assembled

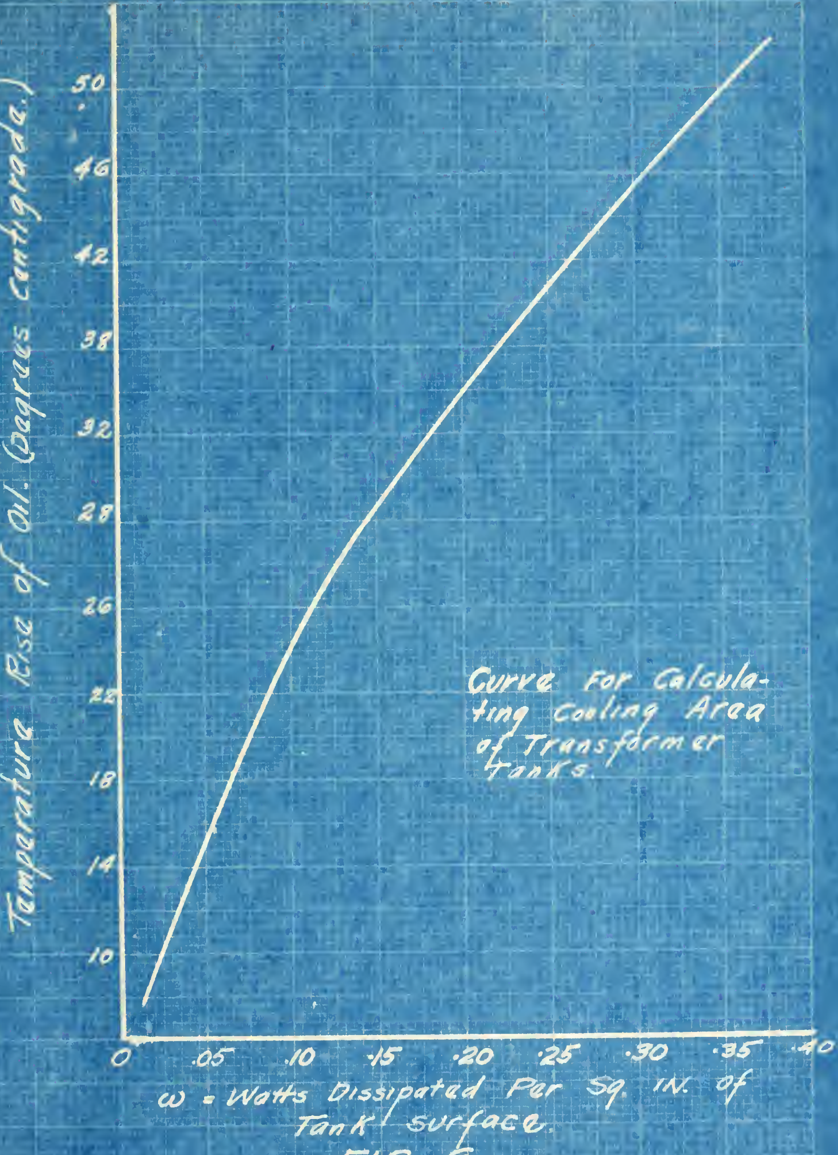

Temperature Rise of Oil. (Degrees Centigrade.)
50
46
42
38
32
28
26
22
18
14
10
0
.05
.10
.15
.20
.25
.30
.35
.40
Curve For Calculating Cooling Area of Transformer Tanks.
ω = Watts Dissipated Per Sq. IN. of Tank surface.

FIG. 6.

stampings is shown in Fig. 7. A tank of circular section 10 feet 6 inches in diameter will accomodate this transformer. The height of the tank (Fig. 8) will now have to be estimated in order to calculate the approximate cooling surface. This height will abe about 240 inches and if we assume a smooth surface (no corrugations), the watts that can be dissipated continuously are

$$0.24 \left[(\pi \times 126 \times 240) + (\pi (126)^2 / 4 \times 2) \right] =$$

92,620; the multiple 0.24 being obtained from the curve in Fig. 6.

The watts to be carried away by the circulating water $(82,400 + 92,300) - 92,620 = 72,080$ watts.

The cooling coil should be constructed preferably of seamless copper tube about 1 1/4 in. in diameter, placed near the top of the tank, but below the surface of the oil. If water is passed thru the coil, heat will be carried away at the rate of 1000 watts for every 3 3/4 gallons flowing per minute when the difference of temperature between the outgoing and ingoing water is 1°C. Allowing 0.25 gallon per minute,

ASSEMBLED STAMPINGS IN TANK OF CIRCULAR SECTION.

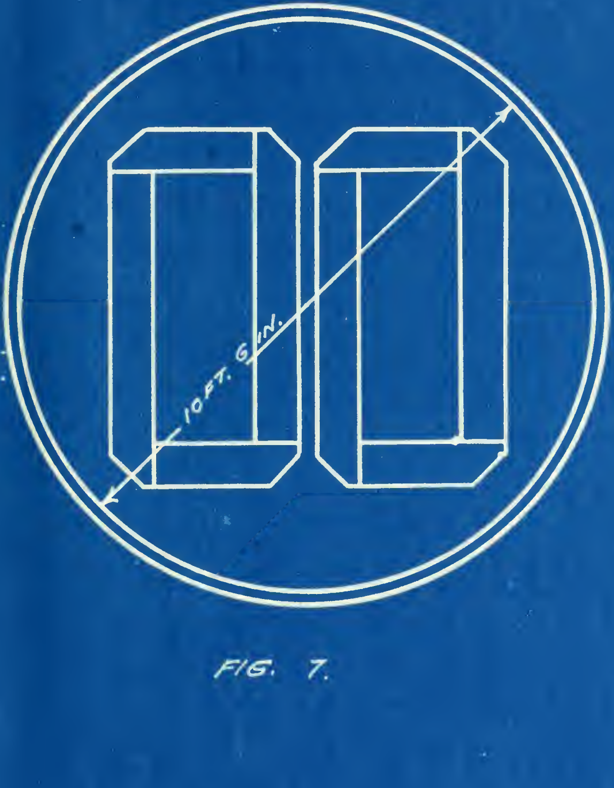


FIG. 7.

per kilowatt, the average temperature rise of the water will be 3.75 / 0.25 = 15° C. A coil made of 1 1/4 in. tube should have a length of 72,080 / 12 x 1.25 x π = say 1500 feet. Assuming the coil to have an average diameter of 9 feet, the number of turns required will be about 1500 / π x 9 = say 53.

On the basis of 1/4 gallon of water per kilowatt, the required rate of flow for an average temperature difference of 15°C between outgoing and ingoing water is 0.25 x 72.08 = 18.02 gallons per minute. This amount may be to be increased unless the pipes are kept clean and free from scale.

The sketch indicates that a tank 240 inches high will accomdate the transformer and cooling coils.

Hottest spot temperature. It is unnecessary to make the calculation for the temperature at the center of the coils, when the surface temperature is known, since the coils are narrow and built up of flat copper strip. There will be no local "hot spots" if adequate ducts for oil circulations are provided around the coils.

Items (62) and (63). Weight of oil and of

complete transformer. The weight of an average quality of transformer oil is about 53 pounds per cubic foot, from which the total weight of oil is found to be about,

$$53 \times (\pi / 4) \times (10.5)^2 \times 20 = 83{,}250 \text{ pounds.}$$

The calculated weights of copper in the windings (Item 49) and iron in the core (Item 40) are 8100 pounds and 46,300 pounds respectively. The sum of these figures is 137,650 pounds. This together with the estimated total of 112,350 pounds to cover the tank, base and cover, cooling coil, terminals, solid insulation, framework, bolts and sundries, brings the weight of the finished transformer up to 250,000 pounds (including oil) or 250,000 / 20,000 = 12.5 pounds per kva of rated full load output.

Mechanical stresses in coils. To determine the approximate pressure tending to force the projecting portion of the secondary end coils outward when a dead short circuit occurs on the transformer. The force in pounds is

$$T \, l \, I_{max} \, B_{Max} \; / \; 8{,}896{,}000$$

where $T = T_2 = T_s / 8 = 560 / 8 = 70$ and l the average length of the portion of a turn project-

ing beyond the stampings at one is, l = 236 / 2 - 46 = 72 inches or 183 cms. The value of the quantities I_{max} and B_{max} depends on the impedance of the transformer. With normal full-load current, the impedance is

$$I_1 Z_p = \sqrt{(530)^2 + (2485)^2} = 2540, \text{ where}$$

~~When~~ the quantities under the radical are the items (53) and (54) of the design sheet. In order to choke back the full impressed voltage, the current would have to be about 110,000 / 2540 = say forty times the normal full load value. Thus the current value for use in the above formula, on the sine wave assumption will be $I_{max} = 43 \times 1818 \times \sqrt{2} = 110{,}000$ amperes. The density of the leakage flux thru the coil is less easily calculated, but since the reactive voltage was calculated on the assumption of flux lines all parallel to the plane of the coil, consider now a path one square centimeter in cross section and of length equal to the depth of the coil, about 54.6 cms., in which the leakage flux will have the average value,

$$B_{max} = 1/2 \left[\left(4\pi / 100\right) \times 70 \times 110{,}000 \times \left(1 / 54.6\right) \right]$$
$$= 8870$$

hence

$$\text{Force in lb.} = \frac{70 \times 183 \times 110{,}000 \times 8870}{8{,}896{,}000}$$

$$= 124{,}180 \text{ pounds.}$$

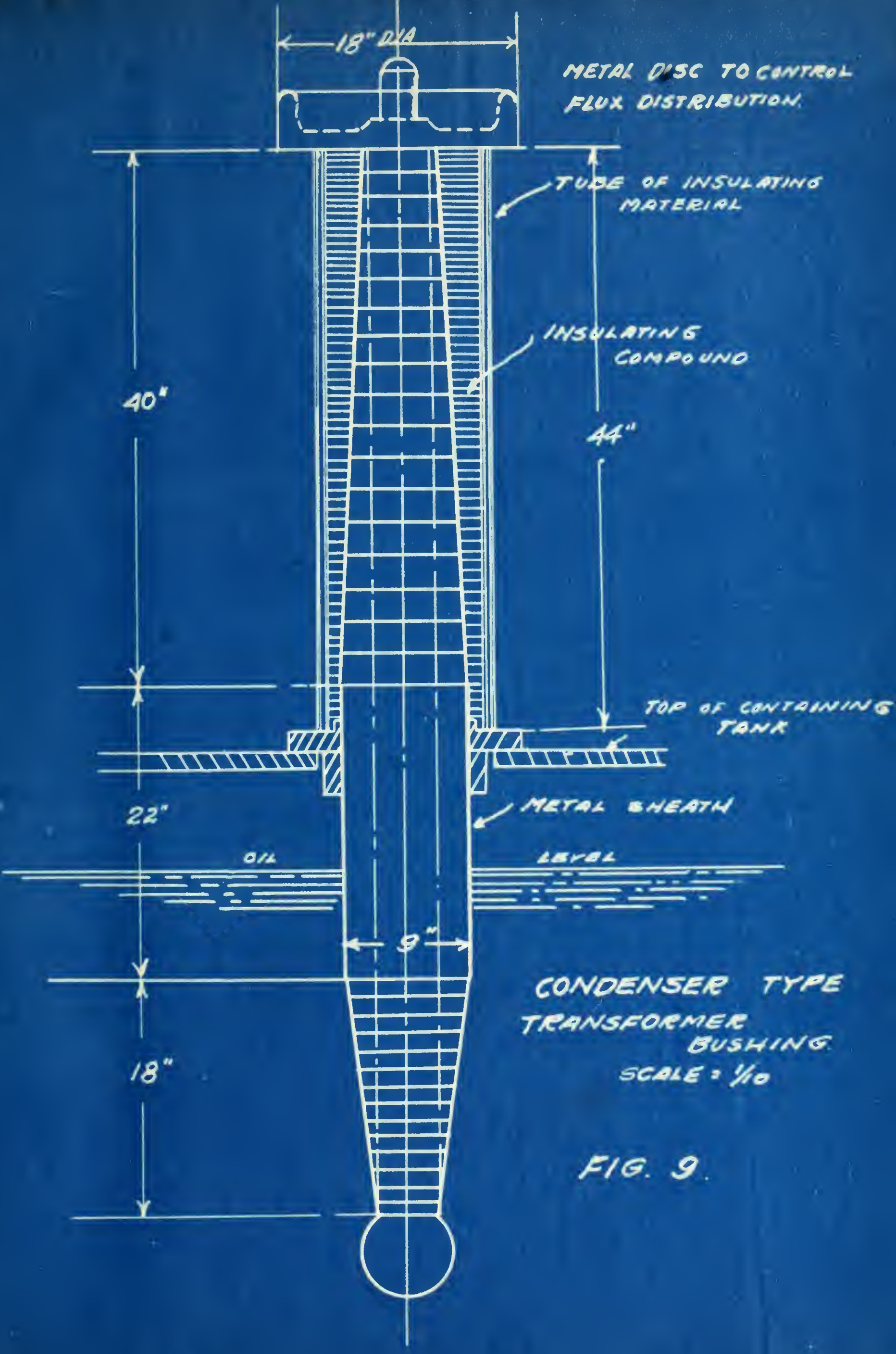
This force is distributed over the whole of the exposed surface of the end coil. An equal force will tend to deflect outward the secondary coil at the other end of the stack. If an arrangement of straps with four bolts is adopted, each bolt must be able to withstand a maximum load of 31,045 pounds.

Condenser Type of Bushing. Assuming working pressure as 110,000 volts and the maximum permissible potential gradient in the dielectric (usually consisting of tightly wound layers of specially treated paper) as 112 kv, the maximum radial thickness of insulation required will be

$$\frac{\text{total volts}}{\text{voltage gradient}} = \frac{387}{112} = 3.45 \text{ cm.}$$

say 1.5 inches to include an ample allowance for the dividing layers of metal oil. (Total volts = E = test voltage x safety factor or $1.25 \times \sqrt{2} \times 220{,}000 = 387$.)

If the inner tube is 3 inches in diameter



CONDENSER TYPE TRANSFORMER BUSHING.
SCALE = 1/10

FIG. 9.

the external diameter over the insulation at the center will be 3 x 3 = 9 inches.

Allow 4000 volts per layer, hence use 28 layers of insuation alternating with 28 layers of tinfoil.

The projection of the terminal above the grounded plate (the cover of the transformer case) need not be so great as would be indicated by the application of the practical rule previously given for surface leakage distance; namely, that this distance should be (0.5 kv/2) in., where kv. stands for the working pressure. The reason why a somewhat shorter distance is permissible is that the surface of the terminal proper has been covered by varnish and asolid compound, and so far as the enclosing cylinder is concerned, the stress along the surface of this cylinder will be fairly uniform, especially if a large flux-control shield is provided, as shown in Fig. 9. In order to avoid the formation of corona at the lower terminal (below the surface of the oil) this end may conveniently be in the form of a sphere.

BIBLIOGRAPHY.

Design of Transformers.

F.W. Carter. A.I.E.E. Vol. 15. Page 639.

Dimension of Single Phase Core and Shell Type Transformers.

A. R. Low. Journal I.E.E. (London) Vol. 43.

The Design of Shell Type Transformers.

R, O. Heller. Journal I.E.E. Vol. 54.

Treatise on Transformers.

Bohle and Robertson.

Design of Static Transformers.

H. M. Hobart.

Design of Electrical Machinery.

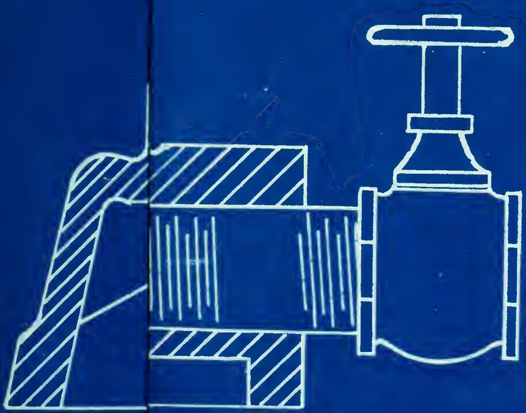
Ryan.

Alternating Current Machinery.

Barr and Archibald.

Electrical Machine Design.

A. Gray



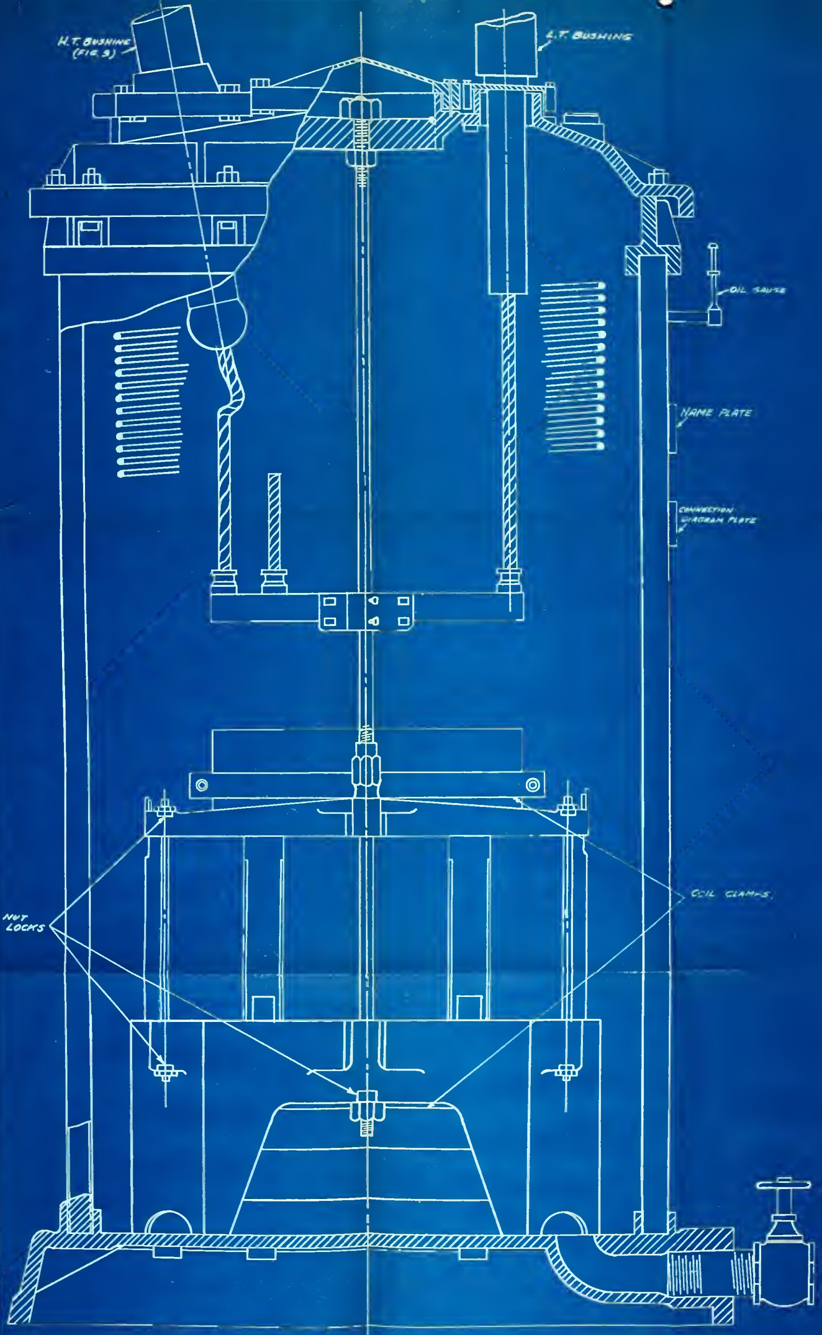

H.T. BUSHING (FIG. 9)
L.T. BUSHING
OIL GAUGE
NAME PLATE
CONNECTION DIAGRAM PLATE
COIL CLAMPS.
NUT LOCKS

FIG. 8.